Coupling Control and Optimization in DLSRs

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ALS-U ADVANCED LIGHT SOURCE

Topics

- Introduction
  - Coupling, Emittance Ratio, Vertical Dispersion
- Correction
  - 3rd Generation Rings
  - Impact on Beamsize Stability + Nonlinear Dynamics
- DLSRs
  - Options for ‘round’ beams
  - Injection + Lifetime Implications
  - Beamsize stability in Rings with large fraction of ID radiation
- Summary

Motivation: Reducing Vertical Emittance

- Vertical emittance of ideal, flat accelerator is very small (for ALS of order of 0.5 pm) – correcting coupling optimizes brightness, potentially by substantial factors – x-ray optics needs to preserve it …
- Simplest errors are tilts of quadrupoles and vertical offsets in sextupoles
- Effects are:
  1. Global coupling (not to be confused with emittance ratio!)
  2. Local coupling
  3. Vertical dispersion
- To optimize performance, usually all three effects have to be corrected simultaneously
- Methods include orbit manipulation, skew quadrupoles, moving of sextupoles, …
- Most successful strategy at light sources: Do not target the three quantities individually, instead use combined approach

Correction Techniques

- One can correct the three coupling effects using skew quadrupoles, vertical offsets (movers or orbit bumps) in sextupoles, steering magnets, …
- The corrections can either target global quantities, local quantities at individual points of the ring, or local quantities everywhere.
  - Coupling correction scales like sqrt of product of beta functions times skew strength.
  - Dispersion correction scales like product of horizontal dispersion times sqrt of vertical beta function time skew quadrupole strength
  - Dispersion' from steering magnets scales like the bending angle.
- Phase advance of coupling (dominant $\mu_x - \mu_y$) and dispersion (μ_y) are different!

Integrated coupling correction

Used accelerator toolbox, Matlab and LOCO for simulations

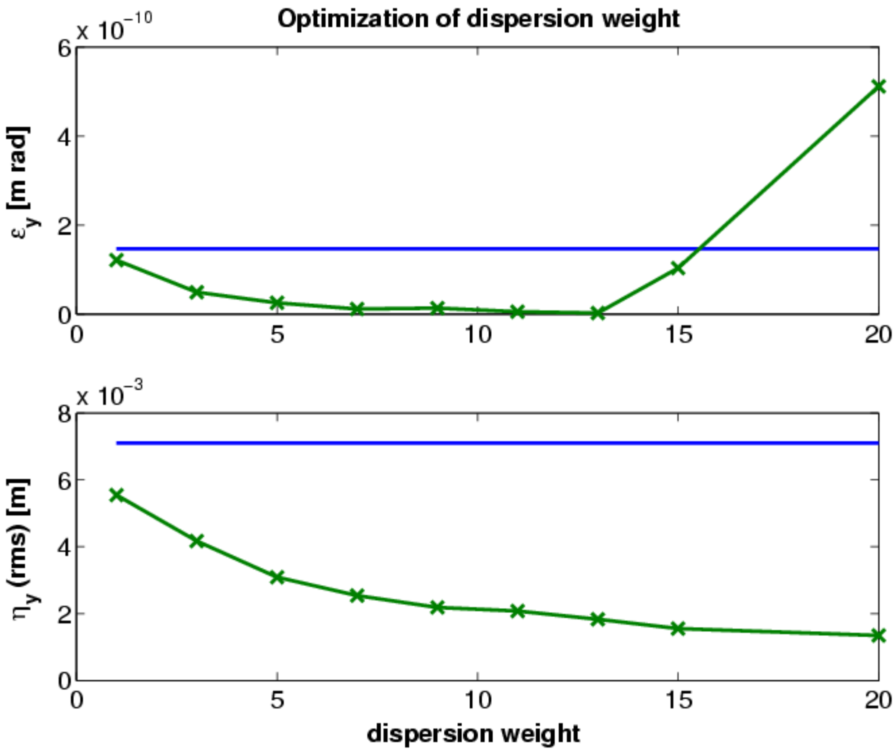
- Simulate many random skew error seeds
- Try to find effective skew corrector distributions and to optimize correction technique in simulation, using two correction approaches:
  1. Response Matrix fitting – 'deterministic', small number of iterations
  2. Direct minimization (nelder-simplex, …) – easy to do on the model, would be difficult on real machine

Both approaches gave about the same performance in our model calculations

- For response matrix analysis you have to optimize several parameters of the code (weight of dispersion, number of SVs, use of effective model/full model …)

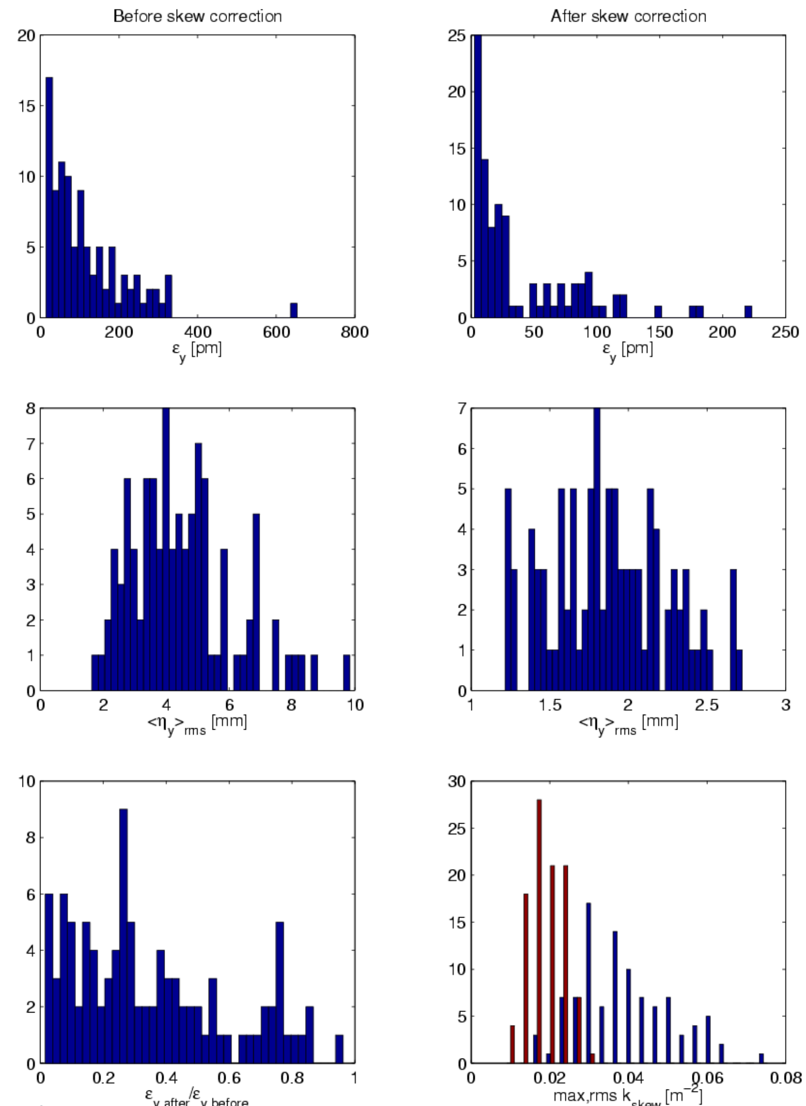
Weight of dispersion in LOCO fit

- The relative contribution of vertical dispersion and coupling to the vertical emittance depends on the particular lattice (and the particular error distribution).
- Therefore the optimum weight for the dispersion in the LOCO fit has to be determined (experimentally or in simulations).
- The larger the weight factor, the better the vertical dispersion gets corrected, but eventually the coupling gets larger.
- Set weight to optimum below that point.



Finding an Effective Skew Quadrupole Set

- To find an effective skew quadrupole distribution, we used several correction methods, first in simulations – best method was orbit response matrix fitting (using LOCO)
- Predictive method, can be easily used on real machine
- Issues are:
  - Cover set of phases relative to dominant coupling resonance(s)
  - Magnets should be distributed around the ring in order to avoid excessive local coupling/vertical dispersion
  - Need different values of dispersion/ beta function to be effective both for coupling and vertical dispersion correction
- Set of 12 skew quadrupoles was already reasonably efficient – nowadays ALS has 48 skews



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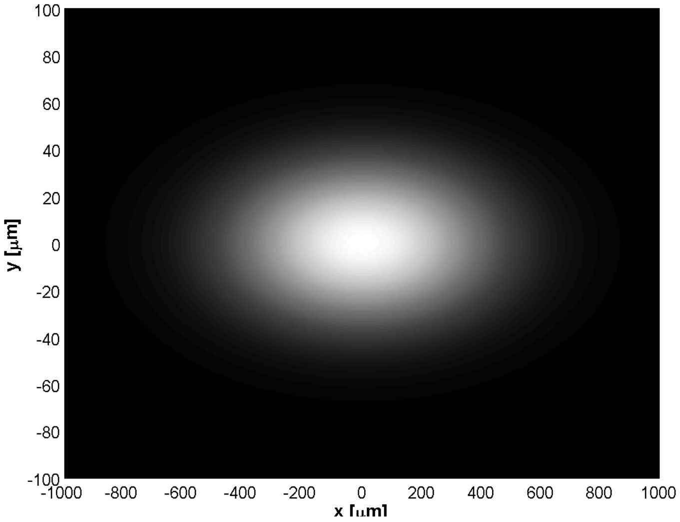
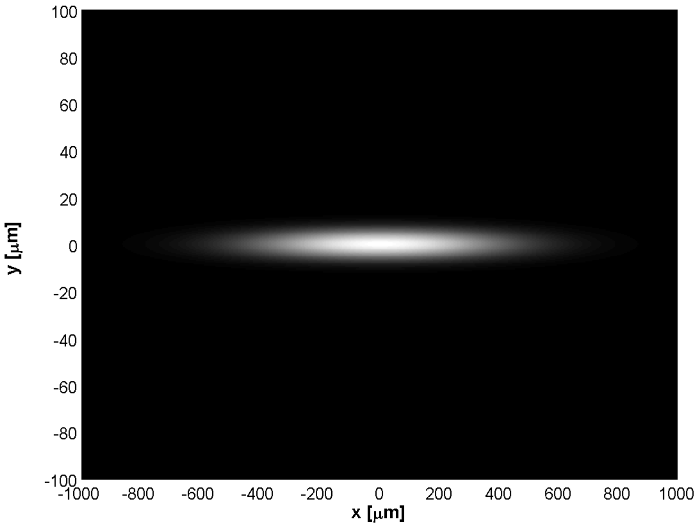
Achieved Emittance Reduction

- Achieved an emittance reduction from 150 pm (prior to top-off) to about 4 pm (2003) and <1 pm (2012).
- Touschek lifetime and user demands motivate routine operation at 20-30 pm, nowadays.
- 4 pm was a world record in 2003 and about the NLC damping ring design value
- Recently repeated with more skew quadrupoles, now reach values below 1 pm, close to the 'quantum limit'.

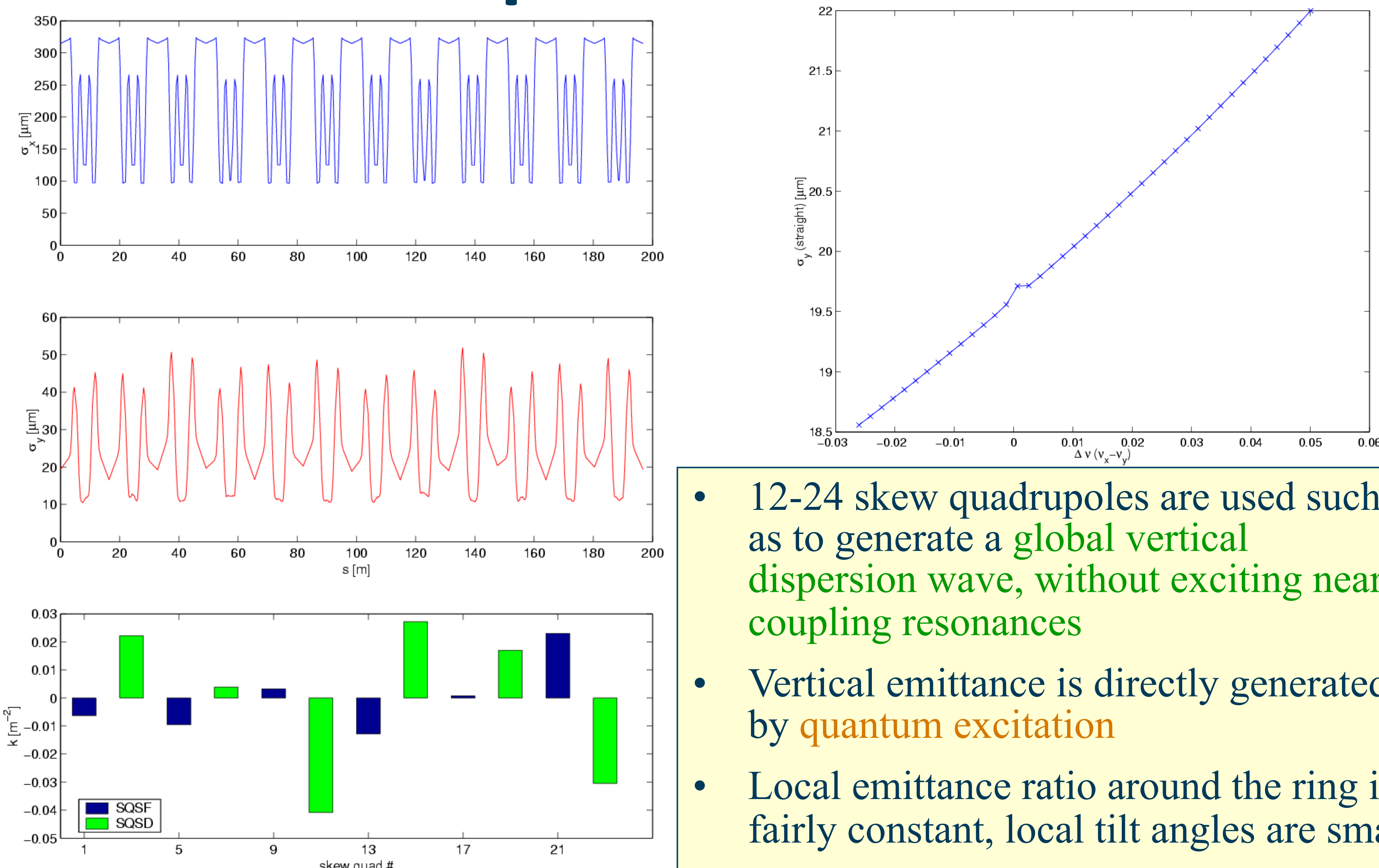




Ways to Increase the Vertical Emittance …

- (Low energy) third generation light sources usually increase the vertical emittance intentionally to achieve acceptable lifetime.
- Historically at the ALS we used a family of skew quadrupoles to excite linear coupling resonance.
- In 2003 we switched to a mode where we correct the coupling and dispersion as well as possible (~1 pm) and then increase the vertical emittance using a global vertical dispersion wave.
- Method has many advantages (beamsize stability, dynamic momentum aperture, …)

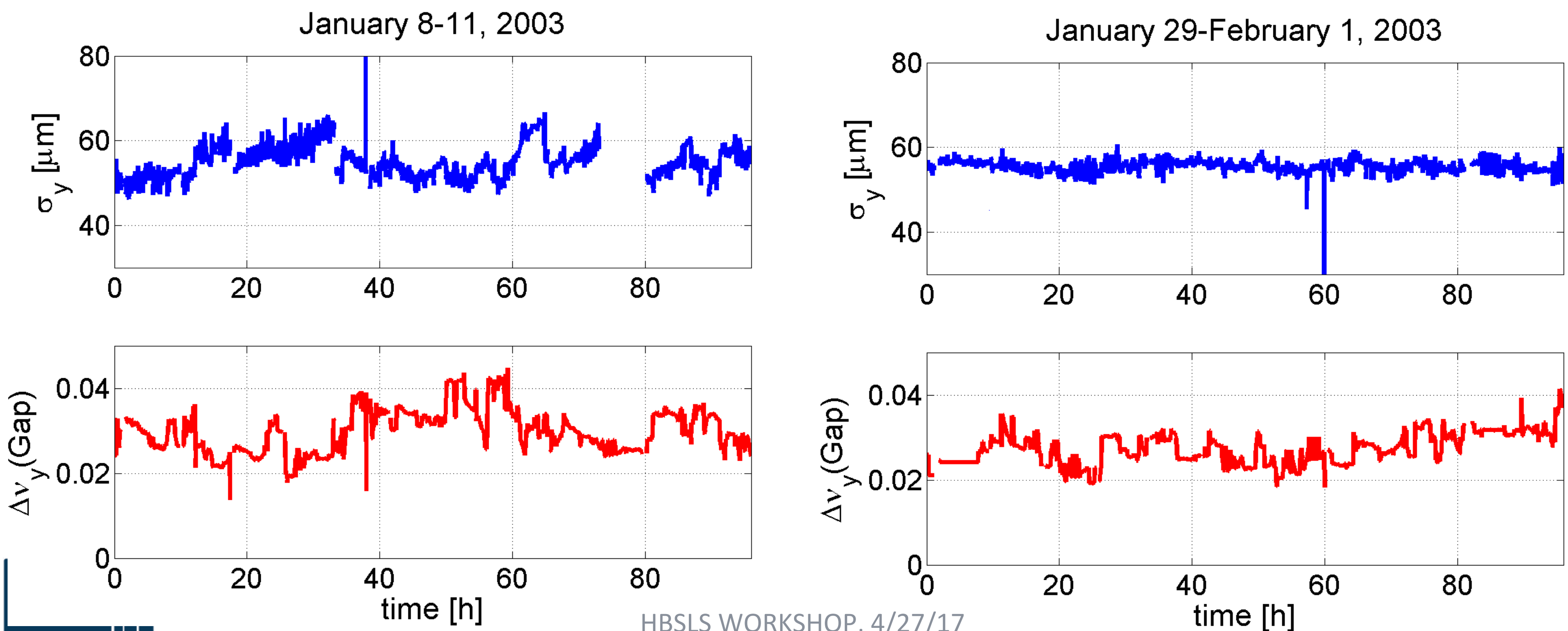
Vertical Dispersion Wave



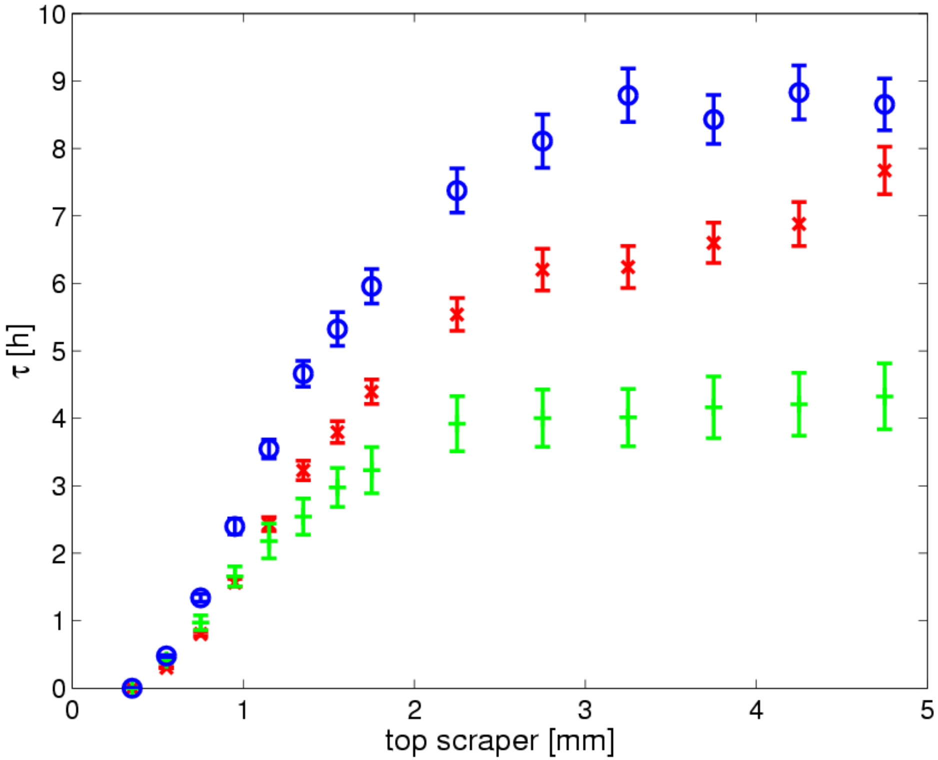
- 12-24 skew quadrupoles are used such, as to generate a global vertical dispersion wave, without exciting nearby coupling resonances
- Vertical emittance is directly generated by quantum excitation
- Local emittance ratio around the ring is fairly constant, local tilt angles are small

Vertical Beamsize Stability

- The stability of the (vertical) beamsize is important for users (not all effects of varying beamsize can be normalized out)
  - Main issues affecting the beamsize are residual tuneshifts (after feedforward compensation) when scanning undulators or skew errors inside those undulators (especially EPUs)
- Using dispersion wave instead of coupling resonance to increase vertical emittance improves beamsize stability



Lifetime vs. Vertical Physical Aperture



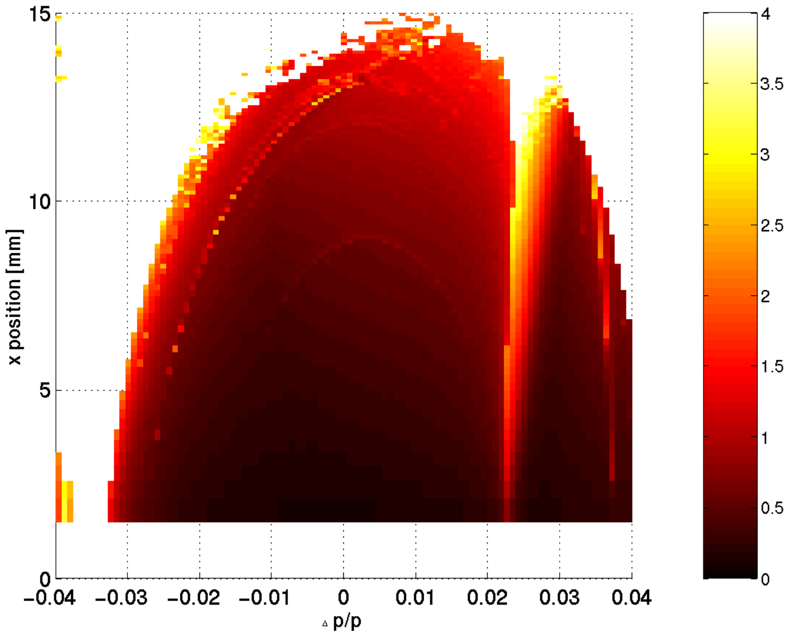
• Performance (Brightness) of undulators/wigglers (both permanent magnet and SC) depends on magnetic gap

• Strong incentive to push physical aperture as low as possible

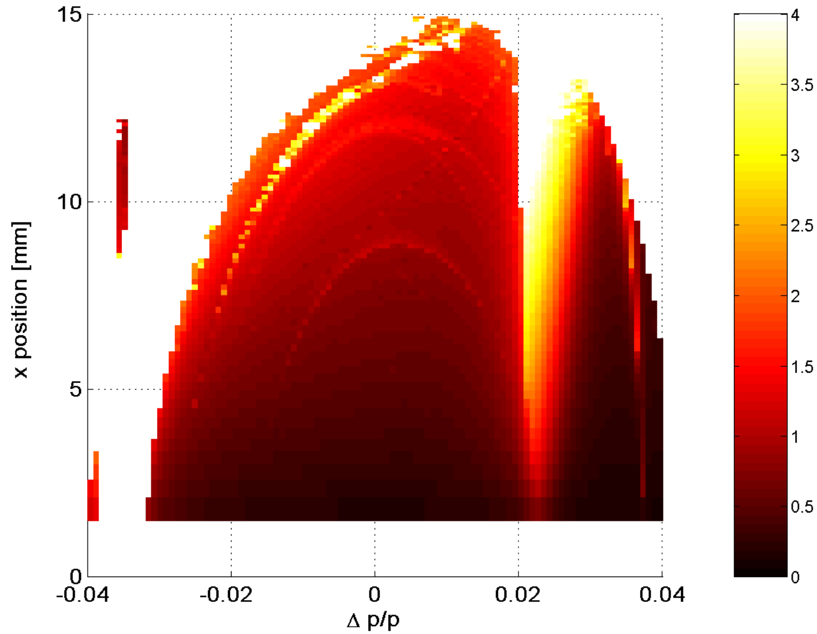
•The vertical physical aperture at which the lifetime starts to get smaller depends strongly on how well global and local coupling is corrected!

Simulation Results (Momentum Aperture – Gap)

Emittance increased using vertical dispersion wave …

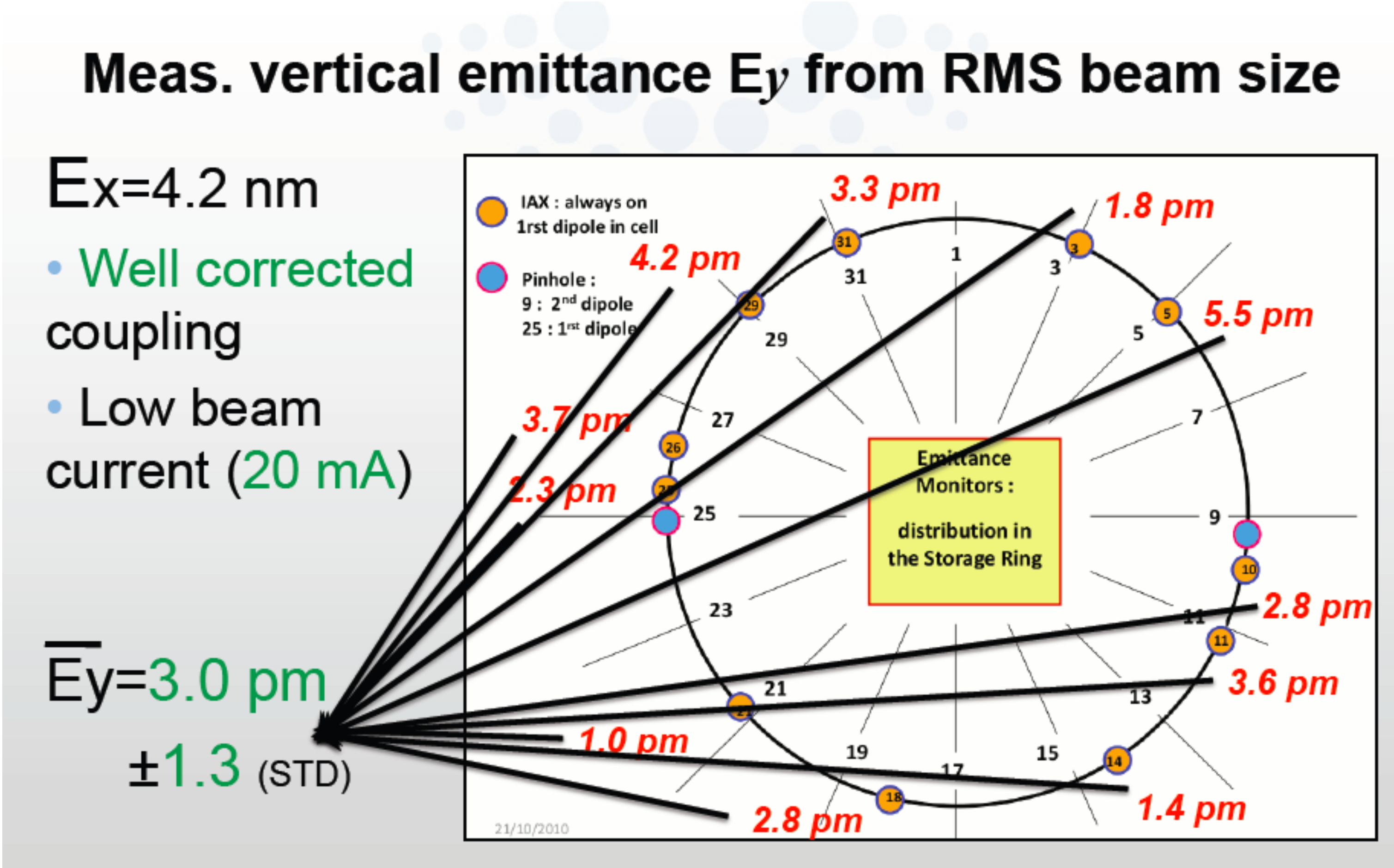


using excitation of coupling resonance



- Tracking results are in good agreement with measured effects, i.e. case with dispersion wave has less yellow and orange areas than the one with excited coupling resonance, indicating less sensitivity to reduced vertical aperture

Other Correction Method: ESRF



(Plots courtesy of A. Franchi)

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ESRF – Resonance Driving Terms

Coupling correction via Resonance Driving Terms

$$f_{\substack{1001\\1010}} = \frac{\sum_{w}^{W} J_{w,1}\sqrt{\beta_x^w \beta_y^w}\, e^{i(\Delta\phi_{w,x} \mp \Delta\phi_{w,y})}}{4(1 - e^{2\pi i (Q_u \mp Q_v)})}$$

1. Build an error lattice model (quad tilts, etc. from Orbit Response Matrix or turn-by-turn BPM data) => RDTs and Dy

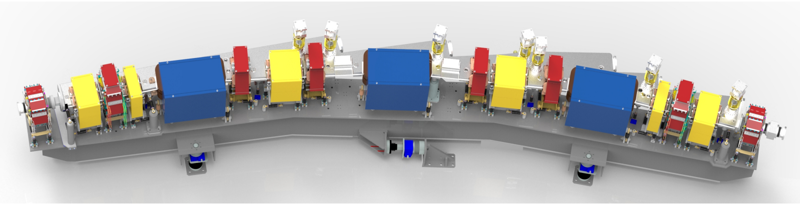
$$\vec{F} = (a_1{*}f_{1001},\ a_1{*}f_{1010},\ a_2{*}Dy)\ ,\quad a_1+a_2=1$$

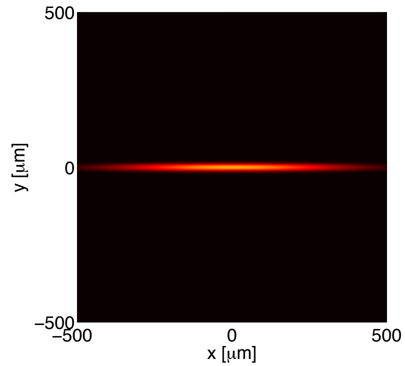
1. Evaluate response matrix of the available skew correctors **M**
2. Find via SVD a corrector setting $\vec{J}$ that minimizes both RDTs and Dy

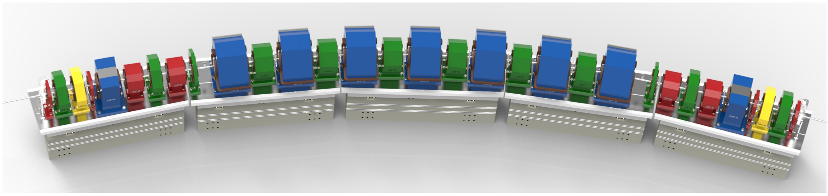
$\vec{J}$ **=-M** $\vec{F}$ **to be pseudo-inverted**

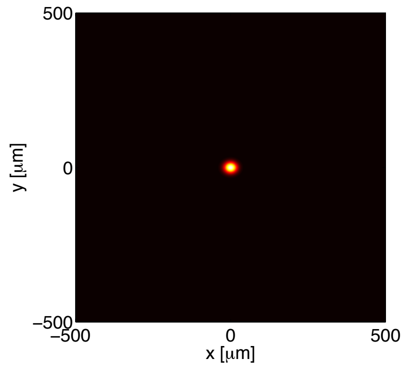
(Plots courtesy of A. Franchi)

DLSRs and round beams









- If beam is truly diffraction limited, there is no benefit from vertical emittance being smaller than horizontal
  – However, definition of ‘diffraction limited’ usually is electron and diffraction emittance being equal, i.e. 25% coherent fraction (2 planes)
- Touschek lifetime, IBS, … would continue to get worse with smaller bunch volume
- Some user experiments (like diffractive imaging, STXM, …) work with round pinholes, would throw away flux if emittances are not equal

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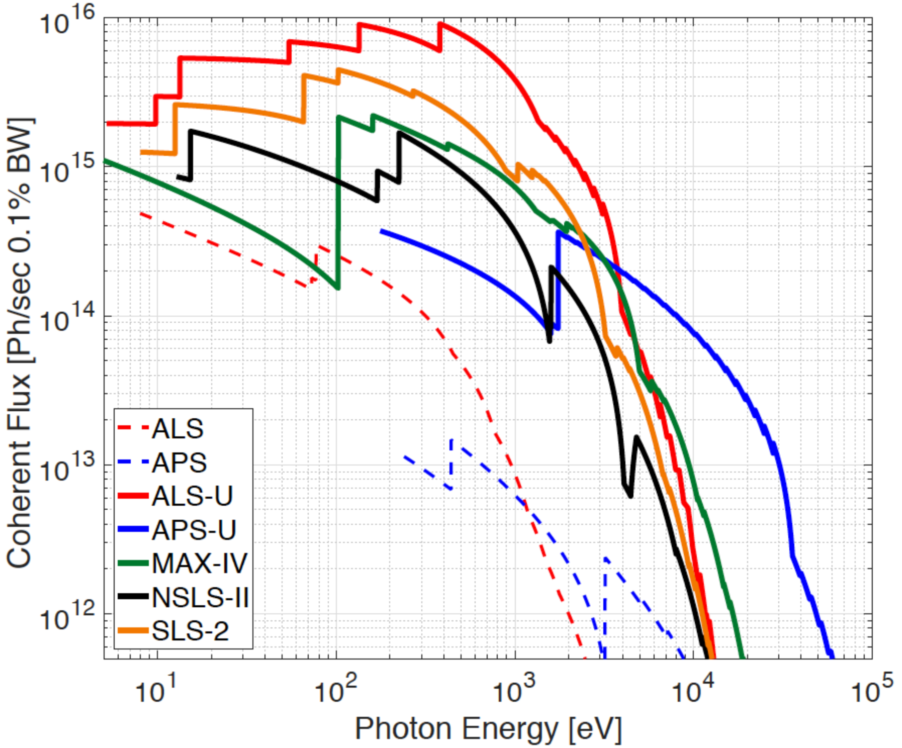
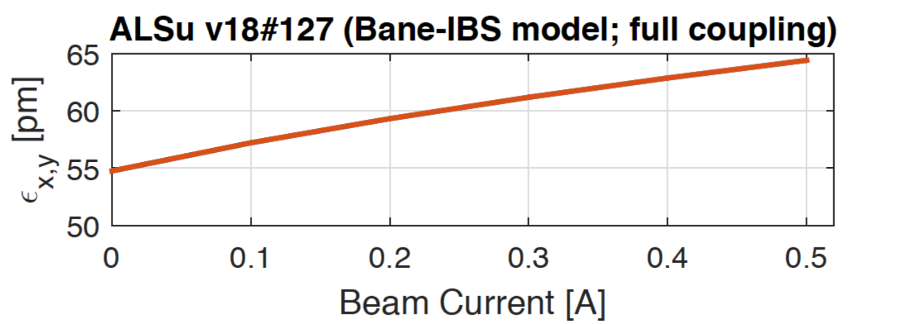
ALS-U: Optimizing for soft x-rays

- Brightness peak in soft x-rays allows low electron beam energy (3 keV-2 GeV)
- Diffraction limited emittance moderate (2 keV-50pm) – reachable with 200m ring
- Vertical plane diffraction limited at same ('large') emittance - round beam
- Lower energy allows shorter focal lengths-more magnets, lower emittance
- Smaller ring → less unit cells → larger dispersion → weaker sextupoles
- Intrabeam scattering much worse-need to fill all buckets and lengthen bunches aggressively
- Heat load on optics smaller for lower beam energy





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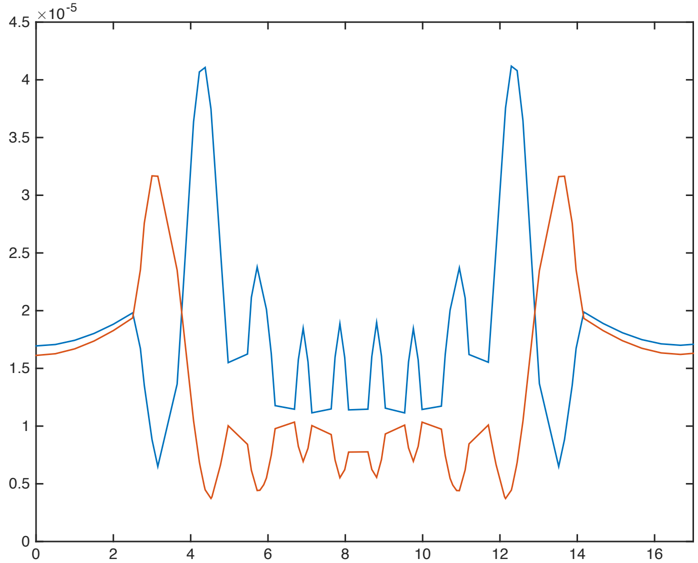
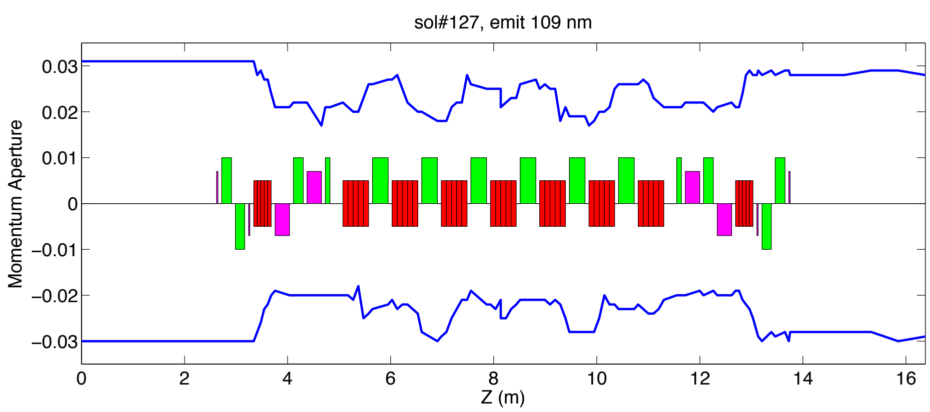
Methods to achieve large emittance ratios in DLSRs

- Damping Wigglers
  - Vertical DW
  - Local vertical dispersion bump in DW
- Möbius Accelerator
- Betatron Coupling
  - Equal fractional tunes
  - Resonance Excitation (time dependent fields)
- Issues to consider: Complexity, Space, Total Emittance, Possibility of different injection schemes, Impact on nonlinear Beam Dynamics, Stability of Emittance

ALS-U example: Coupling Resonance





- Simulated operation on coupling resonance, with moderate coupling errors
- Result are almost equal emittances (60 pm in this case)
- Dynamic and momentum aperture are similar
  - Detuning with amplitude means that coupling at larger amplitude, where it matters for beam losses, does not really change

If Jx > 1, emittance on coupling resonance is > ½ natural emittance

Heuristic model for equilibrium emittances in the presence of coupling

M. Venturini

$$\varepsilon_x' = -\frac{A\varepsilon_x - \varepsilon_y}{T} - \alpha_x(\varepsilon_x - \varepsilon_0)$$
$$\varepsilon_y' = \frac{A\varepsilon_x - \varepsilon_y}{T} - \alpha_y\varepsilon_y$$

Variant of model found in SY Lee's book

- Model gives the expected behavior in the two limiting cases:
  - For $T = \infty$ (no coupling) the x-emittance damps to the natural emittance ε_0 and the vertical emittance to zero)
  - In the absence of damping ($\alpha_x = \alpha_y = 0$) the system admits the fixed-point stationary solution $\varepsilon_y = A\varepsilon_x$, with A depending on vicinity to resonance, strength of linear coupling

- Setting the RHS of both equations to 0 we get the equilibrium emittances in the presence of coupling + damping

From $\frac{A\varepsilon_x-\varepsilon_y}{T} - \alpha_y\varepsilon_y = 0$, ➔ $\varepsilon_y = \frac{A}{1+\alpha_y T}\varepsilon_x \equiv \kappa\varepsilon_x$ (this defines κ)

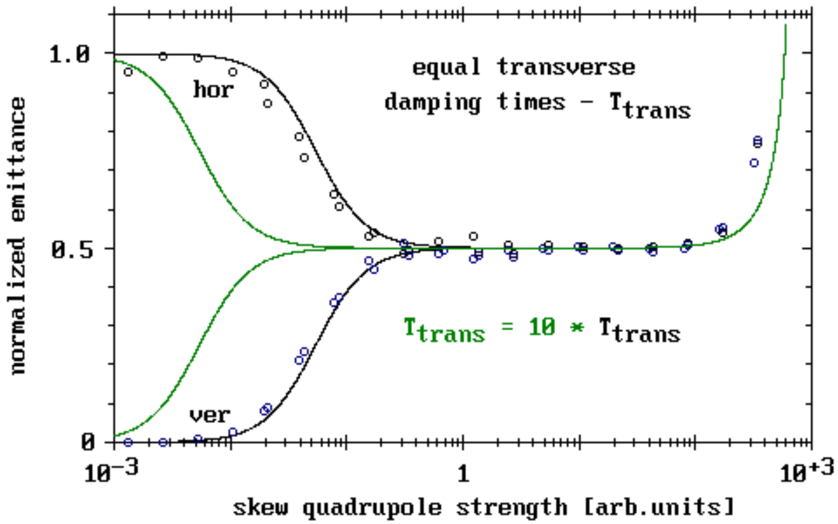
From $-\frac{A\varepsilon_x-\varepsilon_y}{T} - \alpha_x(\varepsilon_x - \varepsilon_0) = 0$ ➔ $\varepsilon_x = \frac{\alpha_x\varepsilon_0}{\kappa\alpha_y+\alpha_x}$

➔ emittance sum: $\varepsilon_x + \varepsilon_y = \varepsilon_x(1+\kappa) = \varepsilon_0\frac{1+\kappa}{1+\kappa(\alpha_y/\alpha_x)}$

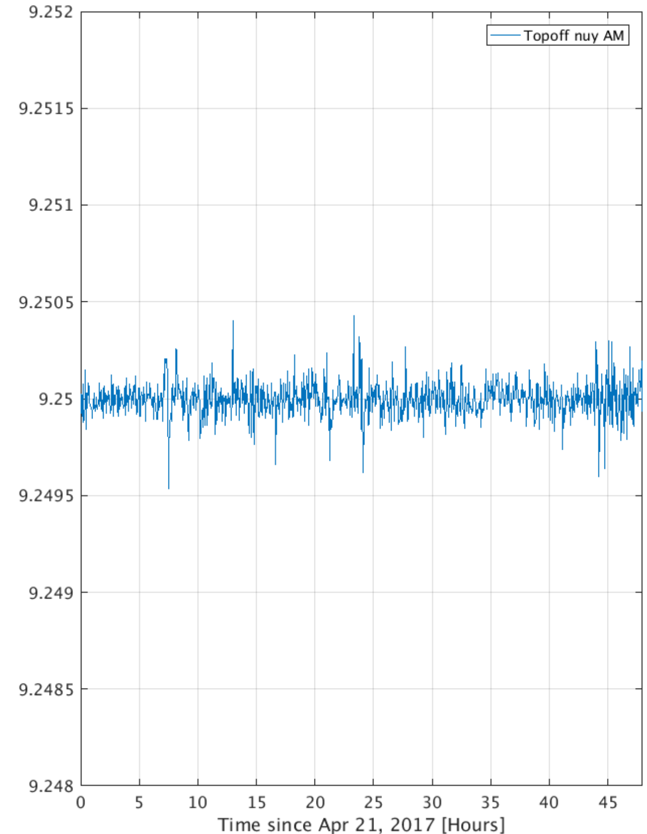
For $\frac{\alpha_y}{\alpha_x} < 1$ the ratio in the RHS of the last Eq. is greater than 1 and therefore $\varepsilon_x + \varepsilon_y > \varepsilon_0$

Beamsize Stability on Coupling Resonance

Peter Kuske



- For equal emittance, fairly insensitive to coupling terms over wide range
- Dependence on tune not too steep for moderate coupling



- ALS example: tune stability with FF and tune FB
- Expect reasonable stability – plan to test on ALS

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Emittance Stability and Undulators

	ε_x [nm rad] Without IBS	With IBS
Bare lattice	0.326	0.453
Bare lattice with LC	0.326	0.372
Lattice with four PMDWs and LC	0.263	0.297
Lattice with four PMDWs, ten IVUs, and LC	0.201	0.231

Max-4 example: S. Leemann, et al., PRSTAB 12, 120701 (2009)

- DLSRs / MBAs / Rings with low average bend magnet field have Beamsize stability issue beyond coupling
- Significant variation of energy loss per turn results in variation of damping times, natural emittance, energy spread
- Extend of effect varies, but can be >20% (including machines already in operation)
- This does not just mean emittance goes down as more undulators are installed, also depends on undulator scans (larger field variation for longer period undulators – ALS: undulator energy loss varies 50% typical week)
- (Additional) Damping wigglers can help in correction, but expensive (cost, space, RF) – full range might not be feasible
  - Other means are less efficient (e.g. limited tunability of MBA lattices)
  - Need to better understand user requirements / impact of uncorrected or partially mitigated

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Summary

- Coupling correction is important to optimize the performance
  - Direct benefit: increased brightness
  - Also improves dynamic (momentum) aperture and therefore injection efficiency and lifetime
- There are several correction methods:
  - Combined approach targeting local coupling, global coupling and vertical dispersion simultaneously is usually used.
  - Using orbit response matrix analysis (LOCO), emittance ratios below 0.1% have been achieved (<1 pm at ALS).
- DLSRs can require larger emittance ratios than currently in use
  - Multiple ways to achieve (including operating on coupling resonance)
  - Beam dynamics impact manageable
  - Beamsize stability requires good tune control, reasonable resonance strength
- Insertion devices provide new challenge if they contribute significantly to total energy loss

Backup Slides

Orbit Response Matrix Analysis: Method

The orbit response matrix is defined as

$$\begin{bmatrix} \vec{x} \\ \vec{y} \end{bmatrix} = M \begin{bmatrix} \vec{\theta}_x \\ \vec{\theta}_y \end{bmatrix}$$

The parameters in a computer model of a storage ring are varied to minimize the χ^2 deviation between the model and measured orbit response matrices (M_{mod} and M_{meas}).

$$\chi^2 = \sum_{i,j} \frac{(M_{ij}^{\mathrm{meas}} - M_{ij}^{\mathrm{model}})^2}{\sigma_i^2} \equiv \sum_{k=i,j} E_k^2$$

The σ_i are the measured noise levels for the BPMs; E is the error vector.

The χ^2 minimization is achieved by iteratively solving the linear equation

$$E_k^{new} = E_k + \frac{\partial E_k}{\partial K_l} \Delta K_l = 0$$

$$-E_k = \frac{\partial E_k}{\partial K_l} \Delta K_l$$

For the changes in the model parameters, K_l, that minimize $||E||^2 = \chi^2$.

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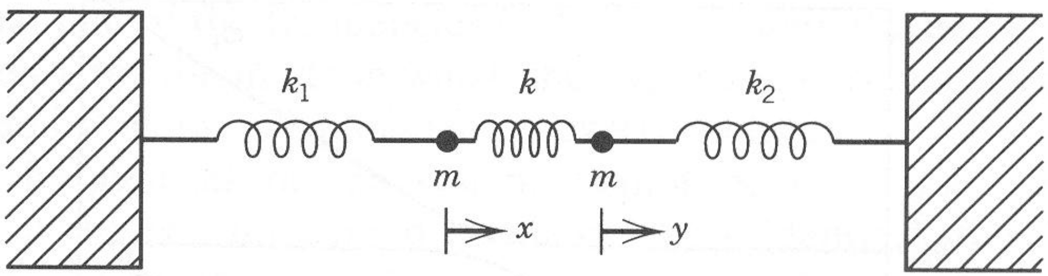
Local/Global Coupling, Vertical Dispersion

- Coupled (Hills) equations of motion :

$$x'' - Kx = -K_s y \qquad\qquad y'' + Ky = -K_s x$$

- With $\quad K = \dfrac{1}{B\rho}\dfrac{\partial B_y}{\partial x} \qquad\qquad K_s = \dfrac{1}{B\rho}\dfrac{\partial B_x}{\partial x}$

- Analogy with mechanical coupled harmonic oscillators (with springs)



$$m\ddot{x} + (k_1 + k)x - ky = 0,$$

$$m\ddot{y} + (k_2 + k)y - kx = 0,$$

Resonance Description of Global Coupling

- Global coupling is typically described using a resonance theory
- Difference coupling resonance

$$\kappa = \frac{1}{4\pi}\int ds\, K_s \sqrt{\beta_x \beta_y}\, \mathrm{e}^{i\phi_D}$$

$$\frac{\phi_D}{2\pi} = \mu_x(s) - \mu_y(s) - \frac{s}{C}\Delta_\mathrm{r} \qquad \Delta_\mathrm{r} = (\nu_x - \nu_y - N)$$

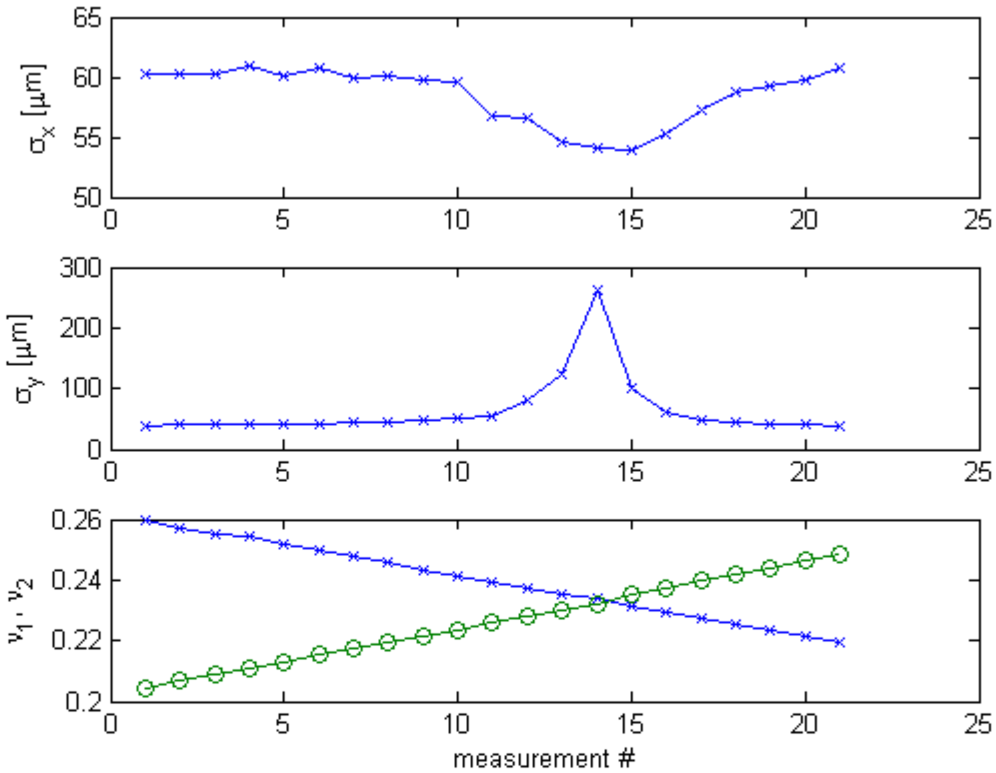
– Vertical emittance near difference resonance:

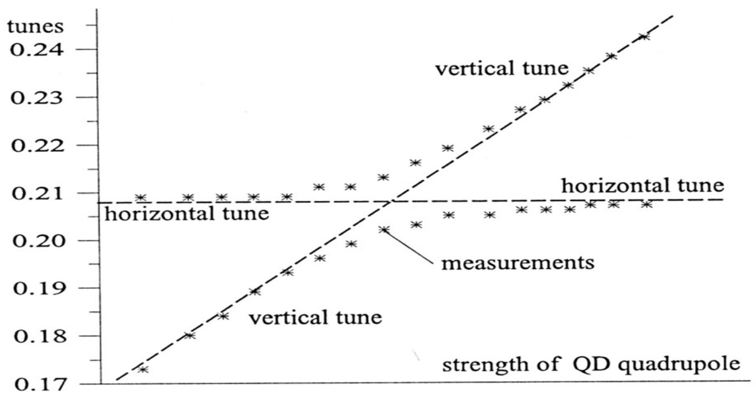
$$\frac{\varepsilon_y}{\varepsilon_x} = \frac{|\kappa|^2}{|\kappa|^2 + \Delta_\mathrm{r}^2/2}$$

κ is resonance strength, Δ_r is distance from resonance.

Scan of Difference Resonance

- There are sum resonances as well (phase advance proportional to sum of horizontal and vertical phase advance) and of course higher order resonances.
- One can create orthogonal knobs of skew quadrupoles directly acting on one of those coupling resonances





- Minimum tune split (on resonance):

$$(\nu_x - \nu_y)_{\min} = 2\,|\,\kappa\,|$$

Normal mode Analysis: C matrix

- Start with 4x4, one-turn matrix $R_{one\text{-}turn}$, which maps the 4 transverse coordinates **x**=(x,x’,y,y’). Normal mode form:

$$\mathbf{R}_{\mathrm{one-turn}} = \mathbf{VUV}^{-1}, \text{normal mode matrix } \mathbf{U} = \begin{pmatrix} \mathbf{A} & \mathbf{0} \\ \mathbf{0} & \mathbf{B} \end{pmatrix},$$

$$\text{with } \mathbf{A} = \begin{pmatrix} \cos\phi_a + \alpha_a \sin\phi_a & \beta_a \sin\phi_a \\ -\gamma_a \sin\phi_a & \cos\phi_a - \alpha_a \sin\phi_a \end{pmatrix},$$

V is of the form (Edwards + Teng)

$$\mathbf{V} = \begin{pmatrix} \gamma\mathbf{I} & \mathbf{C} \\ -\mathbf{C}^{+} & \gamma\mathbf{I} \end{pmatrix},$$

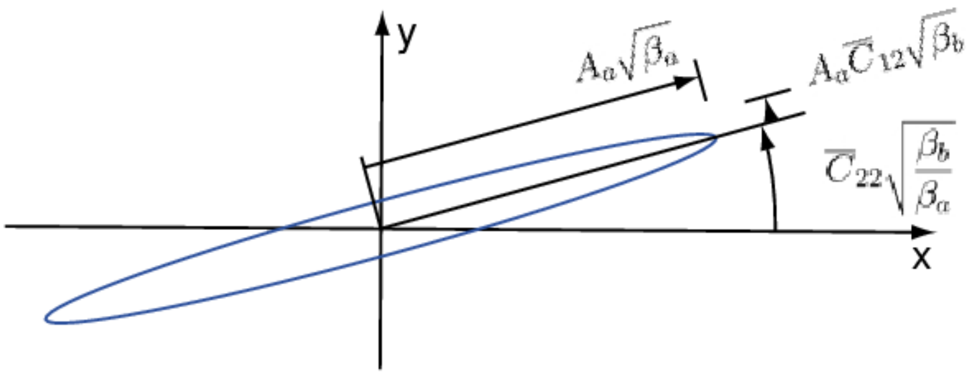
with $\gamma^2 + \left\|\overline{\mathbf{C}}\right\| = 1$. The magnitude of C is a measure of local coupling.

Local Coupling

Often the normalized matrix $\overline{\mathbf{C}}$ is used :

$$\overline{\mathbf{C}} \equiv \mathbf{G}_a \mathbf{C} \mathbf{G}_b^{-1}, \text{where } \mathbf{G}_a = \begin{pmatrix} \frac{1}{\sqrt{\beta_a}} & 0 \\ \frac{\alpha_a}{\sqrt{\beta_a}} & \sqrt{\beta_a} \end{pmatrix}.$$

- Locally there is torsion in addition to the global invariant vertical emittance, resulting in a larger projected emittance:



- Again driving terms scale like the sqrt of the product of the beta functions at the location of the skew errors.

Vertical Dispersion

- There are two main terms that can create vertical dispersion:

$$\eta_y'' + K\eta_y = \frac{1}{\rho_y} - K_s\eta_x$$

  - Dipole errors (steering magnets, misalignments, …) or intentional vertical bending magnets
  - Skew quadrupole fields at the location of horizontal dispersion (due to quadrupole tilts, or vertical offsets in sextupoles)

$$\kappa_{\eta_y} = \int ds\, K_s \eta_x \sqrt{\beta_y}\, e^{i\phi_{\eta_y}}$$

$$\frac{\phi_{\eta_y}}{2\pi} = \mu_y(s) - \frac{s}{C}(\nu_y - 5)$$

- Vertical dispersion directly causes increase of the vertical emittance by quantum excitation

Resonance correction of the sum and difference resonance (global)

To correct coupling, tweak orthogonal harmonic knobs for both difference resonance phases. Minimize tune split.

Sum resonance also generates linear coupling.

$$\kappa_{sum} = \frac{1}{4\pi}\int ds\, K_s \sqrt{\beta_x \beta_y}\, \mathrm{e}^{i\phi_S}$$

$$\frac{\phi_S}{2\pi} = \mu_x(s) + \mu_y(s) - \frac{s}{C}\Delta_{\mathrm{r}} \qquad \Delta_{\mathrm{r}} = (\nu_x + \nu_y - N)$$

Coupling correction – minimize measured vertical beam size as a function of skew quad strengths:

$$\sigma_{y,meas}(K_{s,1}, K_{s,2}, \ldots)$$

One possible method is to use orthogonal harmonic knobs:

$$\sigma_{y,meas}(K_{diff,\cos_N}, K_{diff,\sin_N}, K_{sum,\cos_N}, K_{sum,\sin_N}, K_{\eta_y,\cos_N}, K_{\eta_y,\sin}\ldots)$$

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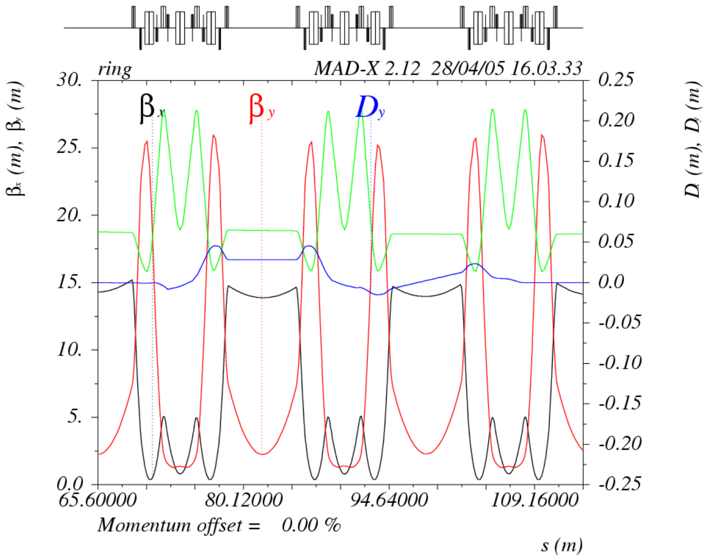
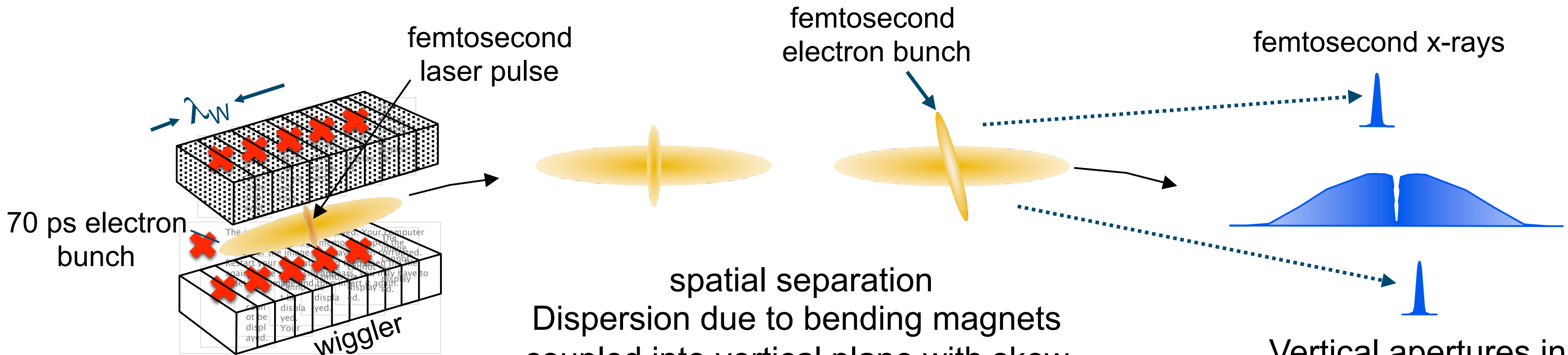
An Extreme Coupling / Dispersion Manipulation Example

- Fs-slicing facility at ALS uses vertical separation -> high field undulator in the middle of a sizeable local vertical dispersion bump
- To keep vertical (natural) emittance constant, whenever this undulator scans, 20 skew quadrupoles around the ring are used to change a global vertical dispersion wave





electron-photon interaction in wiggler

spatial separation
Dispersion due to bending magnets coupled into vertical plane with skew quadrupoles (closed disersion bump).

Vertical apertures in focus plane in undulator beamlines